The Association
of
Engineering and Shipbuilding
Draughtsmen.

ELECTRICAL IGNITION OF AERO ENGINES.

By F. G. SPREADBURY, A.M.Inst.B.E.

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INTRODUCTORY.

THE process of ignition in aero-engines necessitates a regular succession of electrical impulses, in the form of sparks, between the electrodes of the sparking plugs. Such impulses must be synchronously timed with respect to the cylinder piston position, and be accompanied by a sufficiently high voltage to overcome any adverse conditions. The gap between the plug electrodes is, initially, between 0·015 in. and 0·018 in., and may increase to as much as 0·025 in., due to erosion after prolonged use. At the moment the spark is due to occur, the gap is surrounded by a hot gaseous mixture in a state of turbulence at a pressure of the order of seven atmospheres. In order to produce the necessary spark between gaps of the dimensions given above, a voltage of at least 9000 volts must be available. The ignition of petrol air mixtures employed in aero engines requires a certain amount of energy associated with each spark, this amount, however, being far less than is produced by any normal ignition system. Reference to Fig. 1, due to Paterson and Campbell,* shows the energy necessary to fire several different mixtures of petrol and air, and from this it will be seen that the energy is a function of the spark voltage. Comparing Fig. 1 with Fig. 2, which is for a typical aircraft magneto, shows that the energy normally available is of the order of ten times as great as that required.

Although several methods exist of producing electrical ignition, only two are commonly used, one of which is exclusively employed in aircraft, *i.e.*, the magneto. The other method is, of course, the ignition coil. The magneto may be regarded as a particular case of an oscillation transformer. Such transformers normally consist of two electrically-coupled circuits, each circuit possessing resistance, inductance and capacity. On suddenly producing a disturbance in one winding (such as the interruption of a steady current) a transient discharge is set up in both windings, the short life of the discharge being due to the losses in the system. As both circuits possess inductance and capacity, the discharge is generally of an oscillatory character and, having two degrees of

* The characteristics of the spark discharge and its effect in igniting explosive mixtures. By C. C. Paterson and Norman Campbell. E.S.C. Report, No. 23, May, 1918.

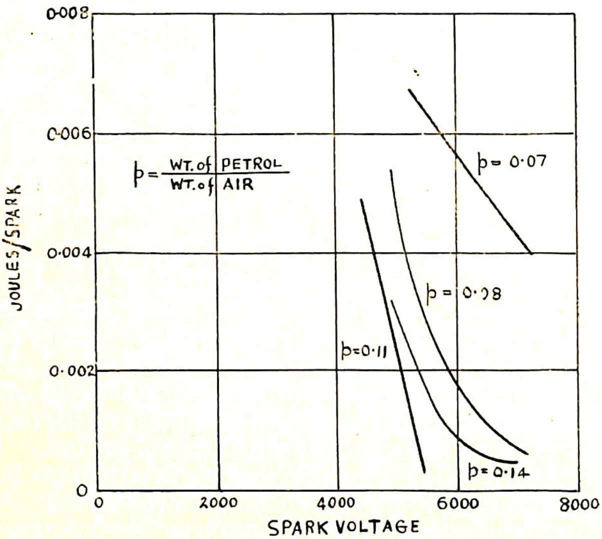
0·008
0·006
0·004
0·002
0
JOULES/SPARK
p = WT. of PETROL / WT. of AIR
p = 0·07
p = 0·08
p = 0·11
p = 0·14
0
2000
4000
6000
8000
SPARK VOLTAGE

Fig. 1.

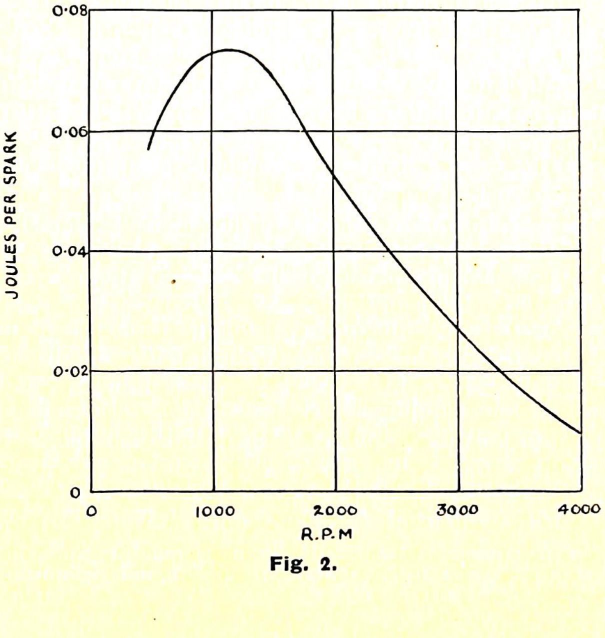
0·08
0·06
0·04
0·02
0
JOULES PER SPARK
0
1000
2000
3000
4000
R.P.M

Fig. 2.

freedom, consists of the superimposition of two components having different amplitudes and frequencies. A typical discharge is shown in Fig. 3, which was produced by interrupting a current in the primary winding of an induction coil. The oscillogram shows the open circuit voltage waveform of the secondary winding, the non-sinusoidal character of which is due to the superimposition of the components mentioned. In the case of the magneto, the windings are very closely coupled, and it will be shown that in these circumstances only a single frequency results. Furthermore, the heavy losses, principally due to the eddy currents in the iron circuit, rapidly damp out the higher frequency component where it tends to exist.

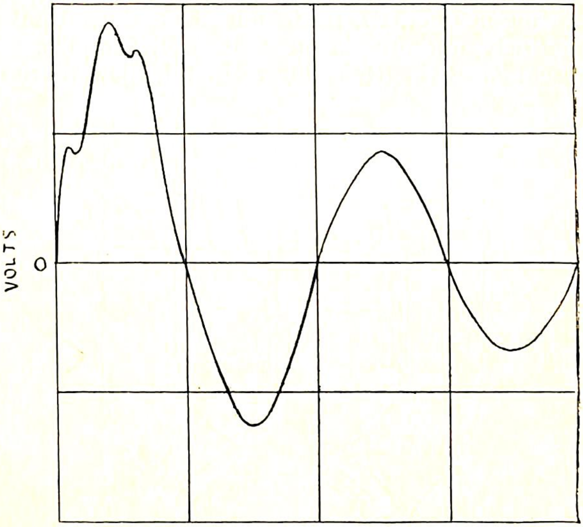

Fig. 3.

Conditions to be fulfilled by Aircraft Magnetos.

The fundamental requirements of aircraft ignition have already been briefly indicated, such requirements, of course, having to be met by the magneto employed. While fulfilling these requirements, the magneto must also satisfy the following conditions :—

It must function satisfactorily at the reduced air densities which are experienced at high altitudes.

It must be capable of not only producing regular spark discharges, but of supplying any leakage current demanded by leaky plugs or atmospheric humidity.

It must be capable of satisfactory operation at temperatures approaching 100°C.

It must not produce radio interference. This involves electrostatically screening the whole ignition system, thus imposing a capacity load on the magneto of from 150 mmfs. to 250 mmfs.

Failure to give regular sparking must not occur at the high speeds associated with multi-cylindered aero engines, especially under power-dive conditions.

Aircraft Magnetos.

Magnetos employed in aircraft are principally of two types, while a third type is occasionally used. These types are known as the rotating magnet, the polar inductor and the rotating armature respectively, and are shown in Figs. 4, 5, and 6. The last-named is seldom used. Referring to Fig. 4, the armature consists

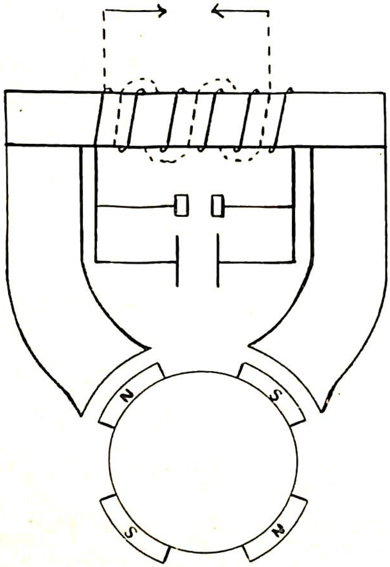

Fig. 4.

of primary and secondary windings wound on a laminated iron structure. The revolving magnet is cylindrical in form, with four poles as shown. These may be formed either by grinding or by fitting laminated poles over a cylindrical piece of magnet material. The air gap between magnet and armature poles is usually about 0·005 in. It is normal practice to close the primary contacts with the rotor in the position shown, and open them when the rotor

has moved approximately 90 electrical degrees from this position. Under these conditions the magneto is said to be fully "advanced," *i.e.*, it corresponds to high-speed running. It will be noted that the contacts are closed when the magnet flux through the armature is a maximum and are opened when the same flux is zero. As this process may be repeated four times per revolution, the same number of sparks may be obtained during this period. The opening and closing of the primary contacts is, of course, effected by a suitable cam.

The flux changes occurring in a typical polar inductor type may be appreciated with the help of Fig. 5. The armature is fitted on a laminated structure as in the rotating magnet type, but the pole shoes in this case are at 180° to each other. At 90°

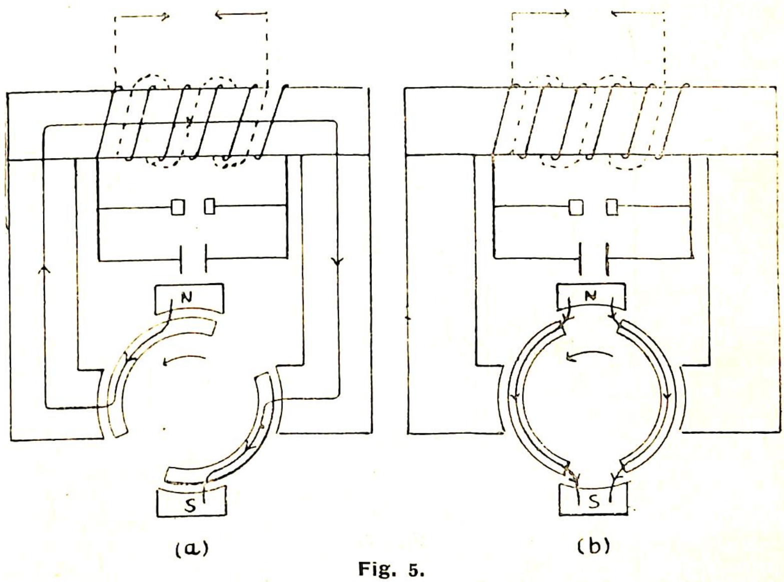

Fig. 5.

to the armature shoes are a similar pair, also making an angle of 180° with each other. These are energised by a pair of stationary magnets. The rotating member consists of two laminated iron inductors, which in (a) are so situated as to cause the flux in the armature core to be a maximum. At (b) the flux distribution is as shown, resulting in an absence of flux in the armature core. It is evident that four complete flux changes are obtained per rotor revolution and hence four sparks may be obtained during this period. The contact breaker points are normally closed at (a) and opened at (b).

The rotating armature type, shown in Fig. 6, is occasionally employed on light aircraft, the positions of maximum and zero flux being that shown and at 90° from that position respectively. The contact breaker normally closes and opens at these positions. It will be noted that only two complete flux cycles can be obtained per revolution, and hence only two sparks may be obtained during this period.

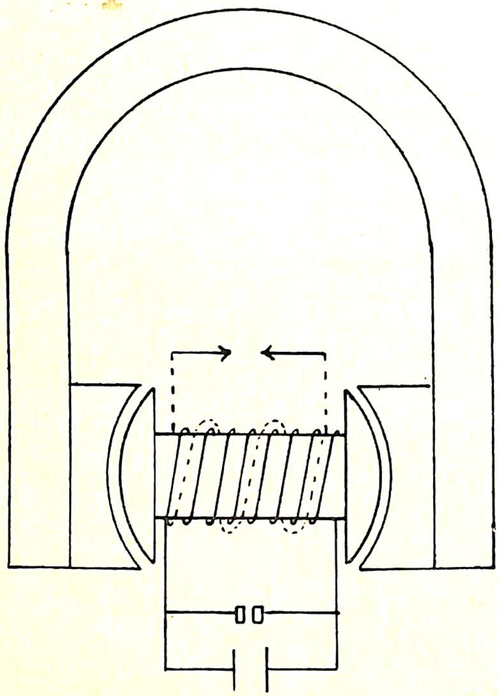

Fig. 6.

The Mechanism of Ignition.

The process of ignition may be considered to consist of two parts :—

(1) That of raising of the secondary self capacitance and its associated circuit to a potential sufficient to break down the spark gap, and

(2) The phenomena which succeed gap breakdown.

It is found that (1) and (2) are so distinctly different that separate methods of treatment are essential to elucidate the effects occurring.

Conditions prior to Gap Rupture.

Prior to breakdown of the spark gap, the circuit conditions may be represented by Fig. 7, where L_1 and L_2 are the coefficients of self-induction of the primary and secondary windings ; C_1 and C_2, the primary and secondary capacities ; M the coefficient of mutual induction between the windings and R_2 the effective resistance of the system. The foregoing conditions represent a modification and simplification of those obtaining in practice, but are justified by the fact that the results deduced therefrom agree reasonably well with those occurring in practice. R_2 represents the total losses in the system, which include the copper losses in both windings, the core eddy current and hysteresis losses, dielectric losses, and any leakage loss, such as that which is often found with sparking plugs. Generally speaking, the core eddy current loss is the most serious of those enumerated. As the windings are invariably closely coupled, it will be assumed in the treatment of the system up to gap rupture that $M/\sqrt{L_1 L_2} = K = 1$, where K is the coupling factor.

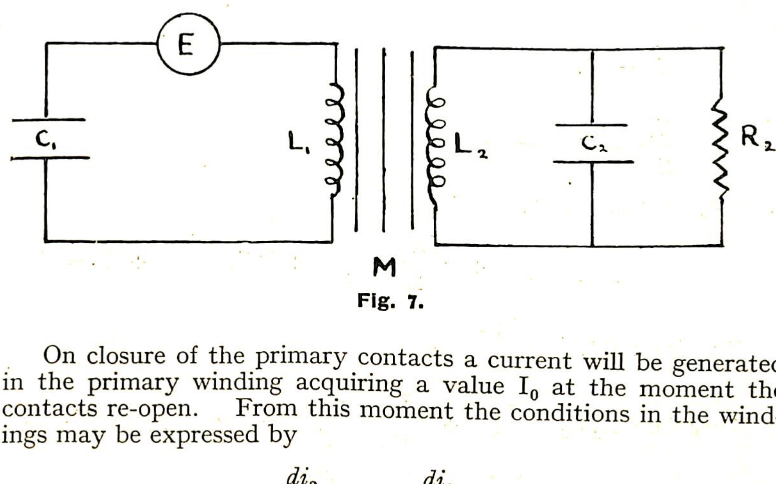

Fig. 7.

On closure of the primary contacts a current will be generated in the primary winding acquiring a value I_0 at the moment the contacts re-open. From this moment the conditions in the windings may be expressed by

$$L_2 \frac{di_2}{dt} + M \frac{di_1}{dt} + V_2 = O \qquad (1)$$

$$L_1 \frac{di_1}{dt} + M \frac{di_2}{dt} + V_1 = E \qquad (2)$$

where i_1 and i_2 are the instantaneous values of the primary and secondary currents, V_1 and V_2 the instantaneous voltages on the primary and secondary capacities and E is the generated primary voltage.

From (2) $$\frac{di_1}{dt} = \frac{E}{L_1} - \frac{V_1}{L_2} - \frac{M}{L_1}\frac{di_2}{dt}$$

and substituting in (1) we obtain

$$V_2 = \frac{M}{L_1}(V_1 - E)$$

or as E is normally negligible compared with V_1,

$$V_2 = \frac{M}{L_1} V_1 \tag{3}$$

Now $M/L_1 = \sqrt{L_2/L_1} = n$, the ratio of the number of secondary to primary turns. Hence, $V_2 = nV_1$

Again,

$$i_2 = C_2\frac{dV_2}{dt} + \frac{V_2}{R_2}$$

$$\frac{di_2}{dt} = C_2\frac{d^2V_2}{dt^2} + \frac{1}{R_2}\frac{dV_2}{dt}$$

$$i_1 = C_1\frac{dV_1}{dt}$$

$$\frac{di_1}{dt} = C_1\frac{d^2V_1}{dt^2}$$

Substituting in (1)

$$L_2 C_2\frac{d^2V_2}{dt^2} + \frac{L_2}{R_2}\frac{dV_2}{dt} + MC_1\frac{d^2V_1}{dt^2} + V_2 = O$$

But from (3), $V_1 = \dfrac{L_1}{M} V_2$

Therefore $$L_2 C_2\frac{d^2V_2}{dt^2} + \frac{L_2}{R_2}\frac{dV_2}{dt} + L_1C_1\frac{d^2V_2}{dt^2} + V_2 = O$$

or $$(L_2C_2 + L_1C_1)\frac{d^2V_2}{dt^2} + \frac{L_2}{R_2}\frac{dV_2}{dt} + V_2 = O$$

Dividing by L_2

$$\left(C_2 + \frac{L_1}{L_2}C_1\right)\frac{d^2V_2}{dt^2} + \frac{1}{R_2}\frac{dV_2}{dt} + \frac{V_2}{L_2} = O$$

Now $L_1/L_2 = 1/n^2$ and therefore the primary condenser C_1 may be replaced by a condenser equal to C_1/n^2 in parallel with the secondary capacity. We then have

$$C \frac{d^2V_2}{dt^2} + \frac{1}{R_2}\frac{dV_2}{dt} + \frac{V_2}{L_2} = O \qquad (4)$$

(where $C = C_2 + C_1/n^2$), the solution of which is

$$V_2 = e^{-\frac{t}{2CR_2}} (A \sin wt + B \cos wt)$$

where $w = \sqrt{\frac{1}{CL_2} - \frac{1}{4C^2R_2^2}}$

The initial conditions are

$$t = O, \quad V_2 = O, \quad dV_2/dt = I_0/nC$$

and in consequence

$$V_2 = e^{-\frac{t}{2CR_2}} \frac{I_0}{nCw} \sin wt \qquad (5)$$

Now $I_0/nC = \frac{I_0}{\sqrt{L_2C}} \sqrt{\frac{L_1}{C}} = \frac{V_0}{\sqrt{L_2C}}$

where V_0 is the maximum voltage attained by V_2 in the absence of all damping. Hence we may write

$$V_2 = e^{-\frac{t}{2CR_2}} \frac{V_0}{\sqrt{L_2}\,C\,w} \sin wt$$

and if $1/L_2C$ is large compared with $1/4C^2R_2^2$, this reduces to

$$V_2 = e^{-\frac{t}{2CR_2}} V_0 \sin wt \qquad (6)$$

From (3) $V_1 = \frac{L_1}{M} V_2 = V_2/n$

Therefore $\quad V_1 = e^{-\frac{t}{2CR_2}} \frac{V_0}{n} \sin wt \qquad (7)$

From (6) and (7) it will be seen that the primary and secondary potentials consist of damped oscillations, the amplitude of the secondary potential being n times that of the primary. These, of course, are the conditions which exist prior to the breakdown of any gap which may be connected to the secondary winding. The frequency of oscillation is given by

$$f = \frac{\sqrt{\frac{1}{CL_2} - \frac{1}{4C^2R_2^2}}}{2\pi} \qquad (8)$$

Figs. 8, 9 and 10 show oscillograms of magneto secondary potentials without gap rupture occurring for various values of resistance shunted across the secondary terminals.

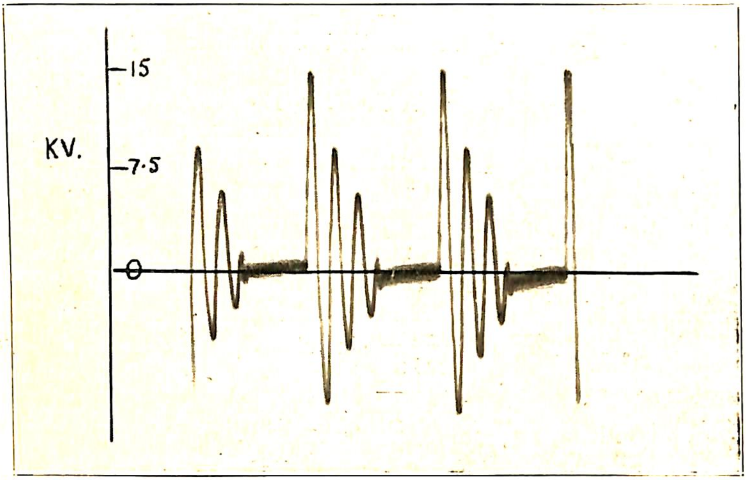

Fig. 8—*Open Circuit Condition.*

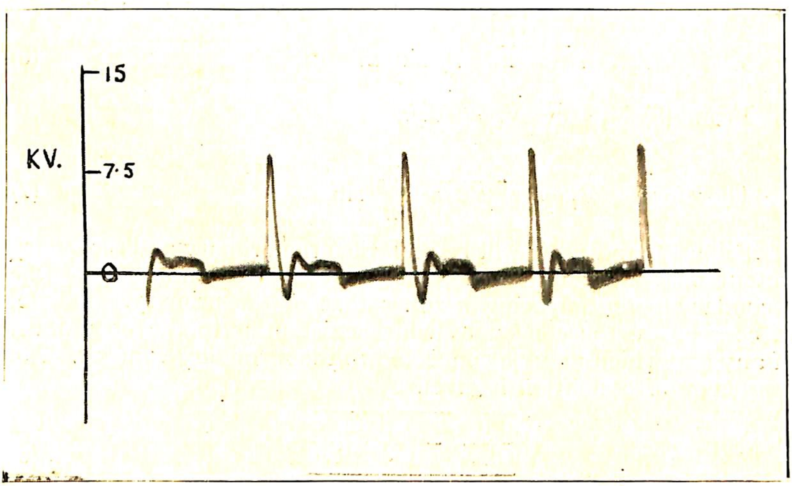

Fig. 9—*With* 0·5 *Megohm.*

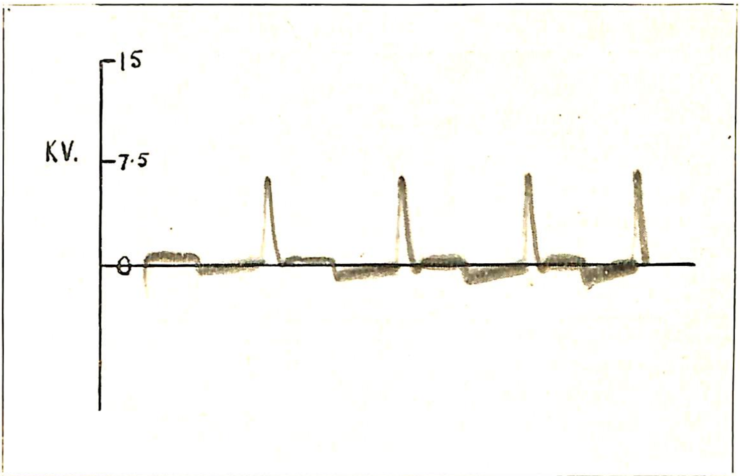

Fig. 10—*With* 0·25 *Megohm.*

It may be noted from (5), that increasing C_1 decreases V_2, and from this it follows that C_1 should be as small as possible consistent with effective contact breaker arc suppression.

Conditions Succeeding Gap Rupture.

It has been shown in the foregoing that on nterruption of a current in the primary winding, the secondary voltage rises in a manner governed by the constants of the coil circuits. Now, if a spark gap is connected across the secondary terminals the secondary voltage, on reaching the gap breakdown potential, will initiate a spark and a set of phenomena entirely different from those just described. Oscillographic studies of magneto discharges through small gaps at atmospheric pressure show that immediately following gap rupture the gap potential falls to a relatively low value of some few hundred volts, at which value it remains roughly constant throughout the life of the discharge. Simultaneously with this, the spark current executes oscillations superimposed on a linearly decaying current. These effeets are demonstrated in Figs. 11 and 12, which were produced by a 12 cylinder aircraft magneto in conjunction with the spark gap of Fig. 29 set to 2·00 mms.

Effect of Gas Pressure on Discharge.

On raising the pressure of the gas surrounding the gap, the current tends to become extinguished in the troughs of the current oscillations shown in Fig. 11. Where extinction occurs, the gap voltage again rises to the breakdown potential, a fresh spark occurs,

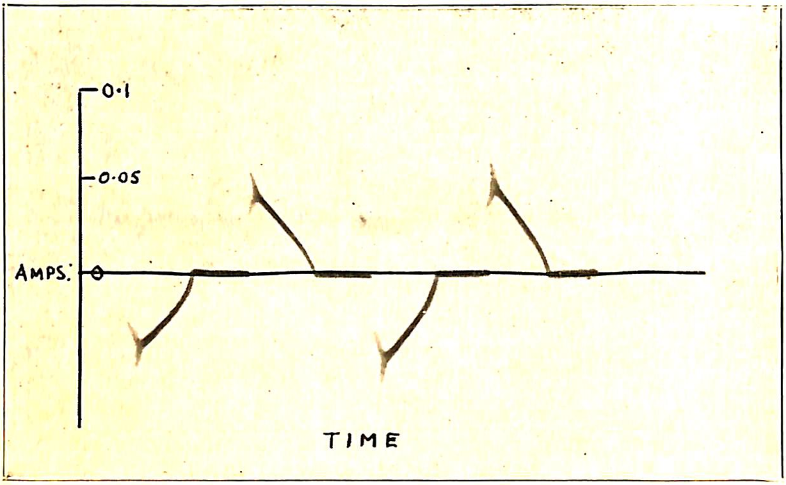

Fig. 11.

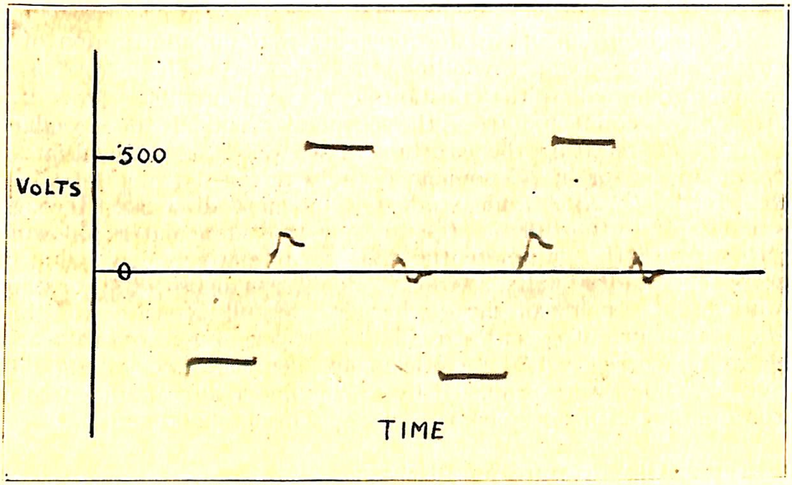

Fig. 12.

and the phenomena are repeated. The effect of an increase in gap pressure above that of the atmosphere then is to tend to cause a rapid succession of sparks at the gap instead of the normal single spark indicated in Figs. 11 and 12. The degree to which this phenomenon occurs is dependent on the gas pressure and the amount of energy furnished by the magneto to the spark gap. The higher the pressure the greater is the tendency for the single spark to break into a series of sparks, while this tendency is diminished by an increase in the magneto energy output.

The following treatment is, strictly speaking, only applicable to magneto discharges through gaps at atmospheric pressure, as it is highly probable that the effects of high gas pressures are not amenable to mathematical analysis.

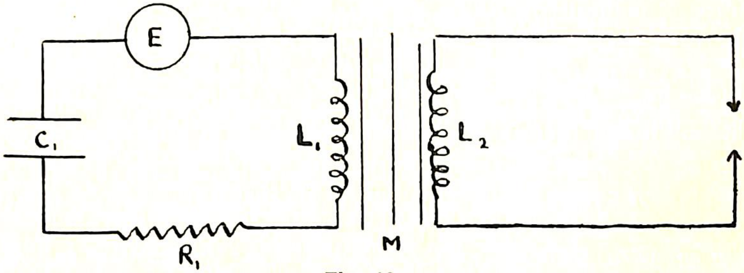

Fig. 13.

The circuit conditions immediately following gap rupture may be represented by Fig. 13. Compared with Fig. 7, it will be noted that the secondary resistance and capacitance are absent and that a resistance, R_1, is included in the primary circuit. As V_2 is approximately constant after gap breakdown, there is no current flow in the secondary capacity C_2. Hence this may be omitted. Furthermore, as the gap resistance falls to a value relatively low compared with R_2, the latter may be neglected. R_1 is the ordinary primary ohmic resistance and must be included for, as will be shown, its absence would result in an undamped oscillatory primary current at contact opening, a condition contrary to experience.

During the life of the discharge the circuit conditions of Fig. 13 may be written :

$$L_2 \frac{di_2}{dt} + M \frac{di_1}{dt} + v_2 = 0 \qquad (9)$$

$$L_1 \frac{di_1}{dt} + M \frac{di_2}{dt} + R_1 i_1 + v_1 = 0 \qquad (10)$$

where v_1 and v_2 are the values of the primary and secondary potentials after gap rupture has occurred.

Differentiating (9) and (10),

$$L_2 \frac{d^2 i_2}{dt^2} + M \frac{d^2 i_1}{dt^2} = O \tag{11}$$

$$L_1 \frac{d^2 i_1}{dt^2} + M \frac{d^2 i_2}{dt^2} + R_1 \frac{di_1}{dt} + \frac{i_1}{C_1} = O \tag{12}$$

From (11), $$\frac{d^2 i_2}{dt^2} = -\frac{M}{L_2} \frac{d^2 i_1}{dt^2}$$

Substituting in (12),

$$\left(L_1 - \frac{M^2}{L_2}\right) \frac{d^2 i_1}{dt^2} + R_1 \frac{di_1}{dt} + \frac{i_1}{C_1} = O$$

or $$(1 - K^2) \frac{d^2 i_1}{dt^2} + \frac{R_1}{L_1} \frac{di_1}{dt} + \frac{i_1}{L_1 C_1} = O \tag{13}$$

Where $K = M/\sqrt{L_1 L_2}$

The solution of (13) is

$$i_1 = e^{-\frac{R_1 t}{2 L_1 (1 - K^2)}} (A \sin wt + B \cos wt) \tag{14}$$

where $$w = \sqrt{\frac{1}{L_1 C_1 (1 - K^2)} - \frac{R_1^2}{4 L_1^2 (1 - K^2)}}$$

Initial Conditions.

In this particular instance time is reckoned from the moment the gap has broken down and the gap voltage has become constant. The primary break current, I_0, will, at this instant, have fallen to some lower value corresponding to the energy acquired by the secondary capacity, C_2, to produce gap breakdown. This energy is equal to $\frac{1}{2} C_2 V_2^2$ and is normally extremely small, about 0·001 joule for a typical case of $C_2 = 0{\cdot}0001$ mf. and $V_2 = 4500$ volts. Assuming $L_1 = 0{\cdot}025$ henry and $I_0 = 3{\cdot}0$ amps., I_0 would only fall to 2·98 amps. in order to produce gap breakdown. Hence for $t = o$, $i_1 = I_0$ approximately. Therefore $B = I_0$.

Again when $t = o$, $di_1/dt = o$, which leads to

$$A = \frac{I_0 R_1}{2 L_1 (1 - K^2) w}$$

In practice the value of A compared with B is invariably negligible, with the result that the sine term in (14) may be neglected. Hence

$$i_1 = e^{-\frac{R_1 t}{2 L_1 (1 - K^2)}} I_0 \cos wt \tag{15}$$

Integrating (9)

$$L_2 \int di_2 + M \int di_1 + \int v_2 \, dt = G$$

or

$$L_2 i_2 + M i_1 + v_2 t = G$$

where G is a constant. Thus

$$i_2 = -\frac{M}{L_2} i_1 - \frac{v_2}{L_2} t + \frac{G}{L_2}$$

When $t = o$, i_1 is equal to I_0 and $i_2 \doteqdot O$

therefore $G = MI_0$

and
$$i_2 = \frac{M}{L_2} I_0 \left(1 - e^{-\frac{R_1 t}{2 L_2 (I - K^2)}} \cos wt\right) - \frac{v_2}{L_2} t \qquad (16)$$

From (10), (15) and (16) we have for v_1, after simplification and discarding terms of negligible magnitude,

$$v_1 = \frac{M}{L_2} v_2 + e^{-\frac{R_1 t}{2 L_2 (1 - K^2)}} L_1 (1 - K^2) I_0 w \sin wt \qquad (17)$$

or
$$v_1 = \frac{M}{L_2} v_2 + e^{-\frac{R_1 t}{2 L_2 (1 - K^2)}} \frac{I_0}{w C_1} \sin wt \qquad (18)$$

From (15), (16) and (18) the importance of R_1 and the necessity of taking into account the fact that K is never unity become apparent; for, although of secondary importance under the conditions preceding gap rupture, the omission of R_1 and the assumption that $K = 1$ after breakdown has occurred, would lead to results completely contradictory to experience. For example, an assumption of perfect coupling ($K = 1$) would lead to results showing: (1) instantaneous collapse of primary current, (2) a linear, ripple-free, decay of secondary current, and (3) a constant value of v_1 during the life of the discharge.

However, with the closely coupled windings employed in aircraft magnetos the life of i_1 is extremely short, and during the greater part of the secondary discharge the primary current is zero and i_2 decays linearly. The time of duration of the discharge is equal to

$$t_d = \frac{M}{v_2} I_0 \text{ seconds} \qquad (19)$$

It will have been noted in the foregoing development of the magneto circuit conditions that the value of I_0, the current at break, is a quantity of fundamental importance. From (6) and (7), V_2 and V_1 are proportional to this quantity, while (15), (16) and (19) show that i_1, i_2 and t_d are important functions of I_0. Furthermore, the energy available for transformation from the primary to secondary winding is equal to $\frac{1}{2} L_1 I_0^2$. The importance of I_0 is clearly such that its establishment must now be considered.

Establishment of Primary Current.

Let the initial position of the rotor be that shown in Fig. 4, and assume that the contact breaker points have just closed. Then, if iron losses be neglected, the E.M.F., E, induced in the primary winding as the rotor rotates is

$$E = i_1 R_1 + L_1 \frac{di_1}{dt} \tag{20}$$

Now $E = n_1 \dfrac{d\phi}{dt} \times 10^{-8}$ volts, so that

$$n_1 \frac{d\phi}{dt} \times 10^{-8} = i_1 R_1 + L_1 \frac{di_1}{dt}$$

$$\text{or} \quad n_1 \frac{d\phi}{dt} \times 10^{-8} - L_1 \frac{di_1}{dt} = i_1 R_1$$

$$= 10^{-8} \left(n_1 \frac{d\phi}{dt} - L_1 \frac{di_1}{dt} 10^8 \right) = i_1 R_1$$

Integrating

$$10^{-8} \Big[n_1\phi - L_1 i_1 \times 10^8 \Big]_{t_2}^{t_1} = R_1 \int_{t_2}^{t_1} i_1 \, dt$$

Now $n_1\phi$ is the flux linkage of the primary due to the magnet, while $L_1 i_1 \times 10^8$ is the flux linkage due to the primary current i_1. When $t = t_1$, the magnet flux through the primary is, say, ϕ_1, while i_1 is zero. At the moment the points are about to open the magnet flux is ϕ_2 while $i_1 = I_0$. Hence

$$10^{-8} \left[n_1 (\phi_1 - \phi_2) - LI_0 \times 10^8 \right] = R_1 \int_{t_2}^{t_1} i_1 \, dt \tag{21}$$

Or the resultant change in primary flux linkage is that necessary to circulate the quantity of electricity $\int_{t_2}^{t_1} i_1 \, dt$ against the primary resistance R_1 during the time of contact closure, $t_2 - t_1$.

If R_1 could be made equal to zero, then

$$I_0 = \frac{n_1 (\phi_2 - \phi_1)}{10^8 L_1} \tag{22}$$

Also, if $(t_2 - t_1)$ is very short, the same result is approximately obtained. The importance of the value of I_0 is determined by the facts that the maximum value of V_2 is proportional to this, and that the spark energy is proportional to I_0^2. It is evident that if a uniform performance is required over the entire speed range at

which the magneto must function, the value of R_1 must be as low as possible. The effect of R_1 may be appreciated from Table 1, which is for a 12-cylinder aircraft magneto having a primary resistance of 0·5 ohm.

TABLE 1.

R.P.M.	I_0 Advance.	I_0 Retard.
300	2·42	1·65
600	2·7	1·95
900	2·93	2·15
1200	3·0	2·33
1500	2·92	2·5
1800	2·9	2·5
2100	2·8	2·5
2400	2·6	2·5
2700	2·42	2·5
3000	2·24	2·5

It will be noted that over a fairly wide speed range I_0 is roughly constant, but falls off at low speeds as the time of closure and the right-hand member of (21) increase.

It has been assumed in the foregoing that L_1, the coefficient of self-induction of the primary winding, is constant. Actually this is not so, as the inductance varies with the value of the current, the magnitude of the magnet flux through the core,* and the position of the rotor. Fig. 14 shows the manner in which L_1

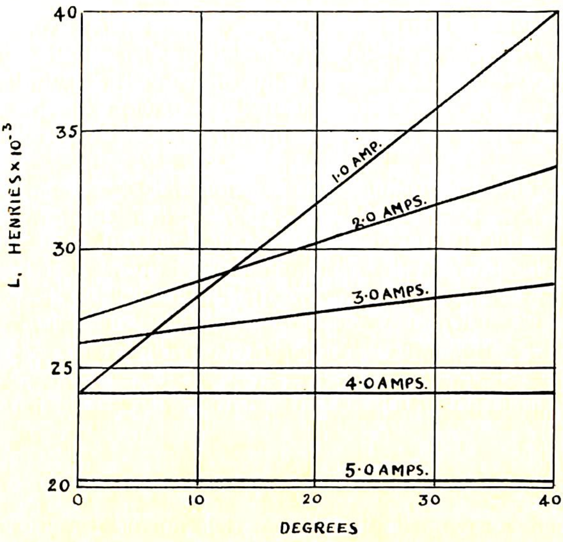

Fig. 14.

* Iron-Cored Inductances, by F. G. Spreadbury. "The Electrical Engineer," Vol. VI., page 768.

varies in a typical case with variations of primary current and rotor position. However, the value of L_1 which is important is that at the moment the contacts separate for the essential condition the current at any instant shall produce a flux equal to the magnet flux change up to that instant.

Hence at any instant the current must be given by

$$i_1 = \frac{n_1 \phi_c}{10^8 L_1} \tag{23}$$

where L_1 is the value of the primary self-induction at that instant and ϕ_c is the change in flux which has occurred since contact closure.

If the primary resistance may be neglected, the waveform of the primary current between contact closure and break may be deduced. Fig. 15 shows a typical magneto flux waveform, and from (22) it is clear that the primary current at any instant is proportional to the magnet flux change which has occurred since contact closure up to that instant. Hence, assuming the contacts to close at zero time in Fig. 15, the successive values of rhe current may be represented by the perpendiculars let fall from the horizontal line $\phi = \phi_1$ on to the flux curve. Thus the primary current waveform is similar to that of the flux curve.

Variable Ignition Timing.

Although many aero engine magnetos work with what is known as "fixed ignition," variable ignition timing is frequently employed. This consists of varying the moment of firing the cylinder charge with respect to the piston position by rotation of the magneto contact breaker, usually through an angle of 30° on a 12-cylinder engine.

The effect of "retarding" the ignition may be considered with the help of Fig. 15. Let it be supposed that the ignition is retarded 60°. Then contact closure occurs at 60° and re-opening at 150°. The flux in the core at closure is now ϕ_3 and in order to trace the current wave a horizontal line must be drawn at this position. The current wave is now of the same shape as that portion of the flux wave lying between the limits ϕ_3 and ϕ_4. It will be noted that in the case considered, the amplitude of the current at break in the retard position is greater than that at advance.

Positions of Contact Closure and Opening.

It has been previously stated that it is normal practice to close the contacts when the magnet flux is a maximum and re-open them when the flux is zero. Consideration of Fig. 15 will show that the position of closure is not critical, due to the flat-topped nature

of the flux wave and the fact that the flux changes very slowly at the nominal point of closure. Hence there is very little disadvantage in closing the contacts at some point later than the nominal position and it is not infrequent to do this at 30° from that position, this corresponding to "fully advanced." An advantage arises from this, the details of which will be given later. It is evident from Fig. 15 that opening the contacts at some point beyond 90° gives an increase in current at break compared with that at the nominal position, and it is usual practice to open the contacts at some 10° or so beyond this position, with the contact breaker fully advanced. There is clearly no advantage in opening them beyond this, as again the flux is changing comparatively slowly. Furthermore, for reasons not yet given, it would be detrimental to other aspects of the magneto's performance.

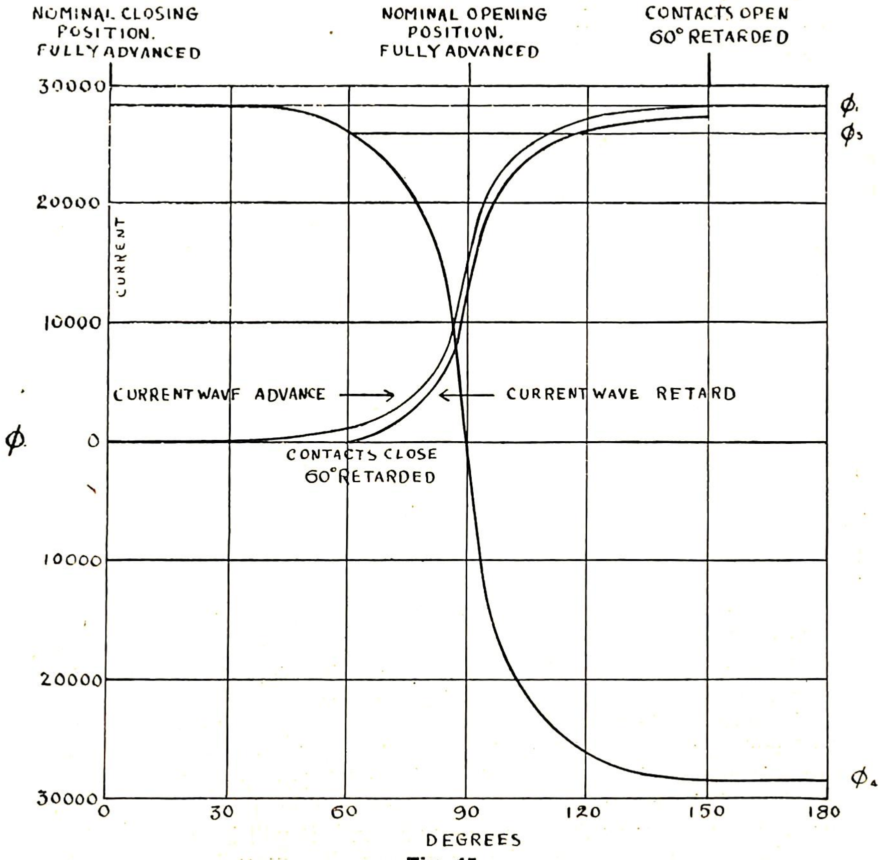

Fig. 15.

Effect of Primary Resistance.

In the foregoing discussion, the influence of the primary resistance on the current has been ignored. Its effect, however, as indicated by (21) is to lower the value of current, for its presence necessitates a resultant flux change in the armature core to circulate the quantity $\int_{t_2}^{t_1} i_1\, dt.$ Hence

$$10^{-8}\,[n_1\,(\phi_1 - \phi_2) + L_1\, I_0 \times 10^8] \neq O$$

which means that I_0 must be less than if R_1 were equal to zero. The effect of R_1 is clearly shown in Fig. 16, which was taken from a magneto in which the contacts were closed for 180°. From 120° it will be noted that the current slowly falls, whereas in accordance with Fig. 15 it should slowly rise. The effect of the falling current is, of course, felt in the retard position, as the contacts usually open when the current is on this part of the curve.

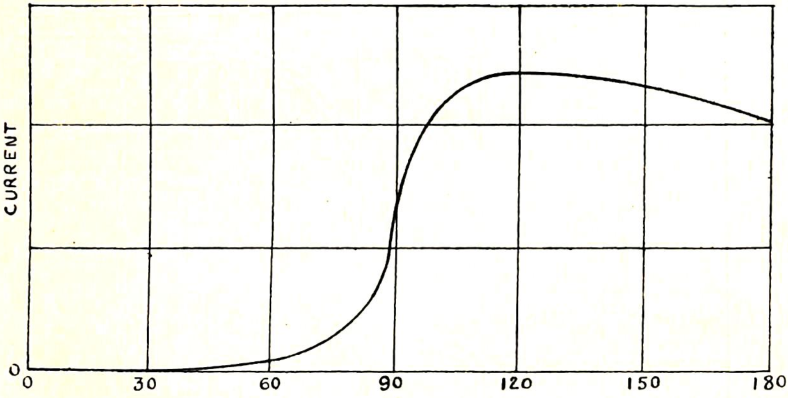

Fig. 16.

The Magneto Contact Breaker.

As previously indicated, the secondary voltage impulse is produced by the interruption of the primary current, this interruption being effected by some form of contact breaker. A typical aircraft magneto contact breaker is shown in Fig. 17. It will be seen to consist of a small pivoted lever carrying a suitable contact and non-metallic "heel." The contacts are closed by means of a leaf spring, the normal force between these being about 2 lbs. The lever is actuated by means of a cam which is mounted on an extension of the rotor shaft. As a magneto may be called upon to produce as many as 500 sparks per second, it will be realised that the frequency of contact breaker operation may be very high.

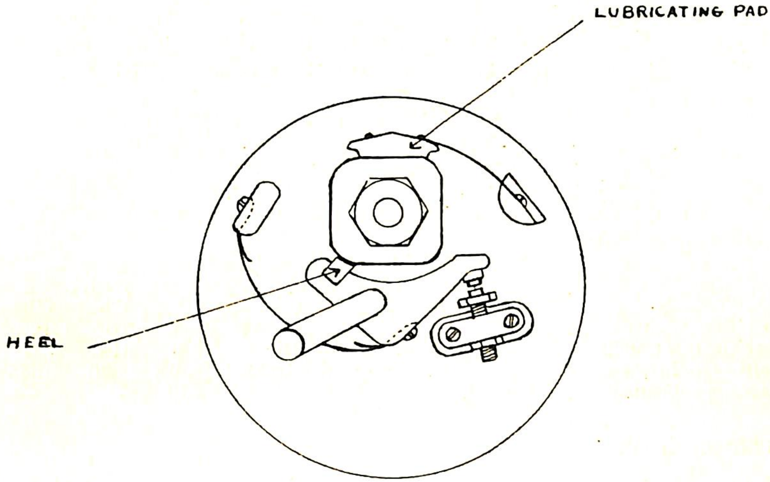

Fig. 17.

Under such conditions there is a tendency for the contacts to bounce on closing and to reduce this tendency it is essential that the moment of inertia of the lever shall be as low as is consistent with mechanical rigidity. The moment of inertia of aircraft magneto contact breaker levers has been reduced to a figure as low as 7×10^{-4} C.G.S. unit. Bouncing may, of course, be reduced by a strong spring, but a limit is set to this by the hammering action of the contacts. Provision must be made for lubricating the cam and heel and is effected in the case shown by a felt pad, soaked with oil, resting on the cam under a light spring pressure.

The Contacts.

The working conditions of the contacts are particularly onerous and their maintenance in a satisfactory condition over long periods is a matter of primary importance. Two metals are in general use for magneto contacts, namely tungsten and an alloy of platinum and iridium. Some physical properties of tungsten are shown in Table 2, while similar properties are shown in Table 3 for different combinations of platinum and iridium. The principal reason for the use of these metals is their hardness and consequent resistance to impact deformation. A disadvantage of tungsten contacts is their tendency to oxidation, the oxide film which may form on the contact surfaces being particularly detrimental in a low resistance circuit such as that of a magneto primary winding. However, their employment is justified by their high melting point and impact resistance. Platinum iridium contacts are relatively free from oxidation, but do not resist impact so successfully as those of

tungsten. The melting point is also much lower. The purpose of alloying platinum with iridium is to increase the hardness, but the alloy becomes unworkable if the iridium exceeds about 30%.

TABLE 2.

Property.	*Unit.*	
Specific weight,	$gm/cm.^3$	19
Specific resistance,	$Microhms/cm.^3$	6
Melting point,	Degrees C.	3380

TABLE 3.

		Composition (per cent. *Ir*).				
Property.	*Unit.*	10	15	20	25	30
Specific weight,	$gm./cm.^3$	21·5	21·54	21·59	21·65	21·7
Specific resistance,	$Microhms/cm.^3$	23·6	29·1	30·6	31·8	33·1
Melting point,	Degrees C.	1800	1820	1850	1870	1885
Hardness (Annealed),	Brinell,	150	190	230	—	—

Contact Erosion.

More serious than the effects of impact are the various types of erosion which occur with magneto contacts. Broadly speaking, there are two essentially different forms of erosion occurring when a pair of contacts make and break a circuit. Upon separation of a pair of contacts which are carrying a current there is an initial increase in contact voltage drop which generally does not exceed about 2·0 volts. This leads to an increase in energy loss at the contact faces, which become heated to the extent that a little of the contact material may fuse at the moment of separation. At separation the gap is exceedingly small, with the result that the potential gradient between the contacts may be very high, perhaps as high as 10^6 volts/cm. As the final point of contact is at an elevated temperature, conditions are suitable for thermionic emission and under the influence of the high potential gradient high-speed primary electrons leave the cathode contact and collide with the anode. This produces positive ions at the latter, which, under the influence of the field, move to the cathode to be there deposited. Under such conditions the effect of continual contact operation is to produce a crater in the positive contact and an excresence on the negative one.

Further separation of the contacts generally reduces the potential gradient and the air and metallic vapour in the gap may considerably hinder the passage of the cathode electrons to the anode. These electrons may ionise the air and metallic vapour and, given suitable conditions, arcing will occur. During arcing it is possible for deposition to take place from cathode to anode, as the bombardment of the cathode by positive ions generally causes greater vaporisation than bombardment of the anode by electrons. If conditions can be so arranged that the initial deposition from anode

to cathode may be neutralised by a subsequent arc, it is probable that a satisfactory condition of the contacts will result. Arcing may, therefore, under certain circumstances, be beneficial.

The Arcless Break.

The function of the condenser which is connected across magneto contact breaker contacts is to secure arcless interruption of the current. From another aspect, as we have already seen, the condenser is detrimental, in that it reduces the maximum secondary potential that can be obtained.

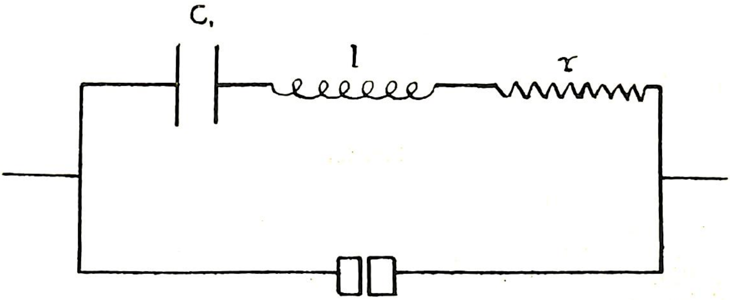

Fig. 18.

In order to study the contact effects occurring at break, it is sufficient to consider the circuit of Fig. 18. I_a and I_c are the arc and condenser currents at any instant, r and l any inductance and resistance in the condenser circuit, while I_0 is the magneto primary winding current, assumed constant for the period under consideration. The assumption that I_0 is constant is justified, as only a small gap separation, and consequently a short time, are involved. For arcs of lengths usually found in ordinary practice, the relationship between the various quantities involved may be expressed by

$$V = \alpha + \frac{\beta}{i} + (\gamma + \frac{\delta}{i})\ L$$

where V and i are the arc voltage and current respectively, L the arc length, and α, β, γ and δ are constants. For the very small arc lengths occurring at magneto contacts it is probable that this relationship does not hold and that the connection between voltage and current is better expressed by what is known as the minimal arc characteristic.*

This characteristic, shown in Fig. 19 for platinum contacts, concerns arcs between gaps of indefinitely small lengths, hence the term "minimal."

* Minimal Arc Characteristics, by H. E. Ives, "Journal of the Franklin Institute," October, 1924.

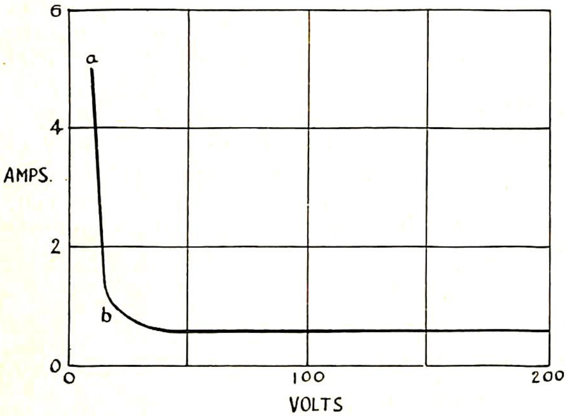

Fig. 19.

Referring to Fig. 19, it will be noted that the arc voltage remains roughly constant until the arc current falls to such a value that extinction starts to occur. At this point, about 0·8 amp., the arc potential rapidly rises, corresponding to rapid decay of the remaining arc current. Assuming the contacts to be shunted by the circuit shown in Fig. 18, the conditions while operating on that part of the minimal arc characteristic, *ab*, may be expressed by

$$V_c + l\frac{d\,I_c}{dt} + I_c r = V$$

or
$$l\frac{d^2 I_c}{dt^2} + r\frac{d\,I_c}{dt} + \frac{I_c}{C_1} = O \qquad (24)$$

where V_c is the voltage on the condenser, I_c, the condenser current, and V, the arc voltage (roughly constant at about 15 volts).

The solution of (24) is

$$I_c = e^{-\frac{rt}{2l}}\frac{V}{l\,p}\sin pt \qquad (25)$$

from which it follows that the arc current is given by

$$I_a = I_0 - e^{-\frac{rt}{2l}}\frac{V}{l\,p}\sin pt$$

or
$$I_0 - e^{-\frac{rt}{2l}}\,V\sqrt{\frac{C_1}{l}}\sin pt \qquad (26)$$

$$p \text{ is equal to } \sqrt{\frac{1}{l\,C_1} - \frac{r^2}{4\,l^2}}$$

In order that the arc duration shall be as short as possible, it is evident that the maximum value of the second term in (26) shall be as large as possible and rapidly reduce the arc current to the point at which extinction starts to occur. At this point the arc voltage rapidly rises, resulting in a rapid transference of current to the condenser, the conditions expressed by (26), of course, no longer being applicable. To ensure the foregoing, it is essential that r and l shall be as small as possible, while C_1 must not be below a certain figure depending on the value of I_0. The usual value of C_1 is from 0·1 to 0·2 mfs. r and l are kept to a low value by having the connections between the condenser and contact breaker as short as possible. In the event of C_1, r and l being such that I_a is not reduced to the extinction value at the time of the first maximum of (25), a sustained arc will occur until such time as the contacts separate beyond minimal distances or I_0 drops below the value necessary to sustain the arc.

From the foregoing, it is evident that the term "arcless break" is something of a misnomer. It is usually applied to the very short period arc which results from satisfactory values of I_0, C_1, etc., as distinct from values which produce a sustained arc. In the latter case the arc may last several milli-seconds, whereas in the former the period may only amount to a few micro-seconds.

Effects of Braided Cable.

It has been stated previously that aircraft magnetos must not produce radio interference and that this necessitates screening the whole ignition system. The screening, in particular, which must be carried out is that of the distributor and H.T. cables. The former is usually enclosed in an aluminium cover, while the latter are either covered with copper braid or enclosed in a manifold. The effect is to impose a capacity load on the magneto of from 150 to 250 mmfs. An examination of the effect of an increase in C in (5) shows that there is a reduction in V_2, while a change in C, due to an increase in secondary capacity, is without effect once gap rupture has occurred. Fig. 20 gives the values of V_2 for a magneto fitted, first with unbraided cable, and then with 6-ft. of metal-braided cable corresponding to a load of 250 mmfs. A further effect of the added secondary capacity produced by metal-braided cables is an increase in sparking plug electrode erosion. This effect is roughly proportional to the length of braided cable employed and in a particular instance was $2\frac{1}{2}$ times that occurring with plain cables. The cable length was 9 ft.

Altitude Effects.

When an ignition system operates in the rarified air of high altitudes, a number of phenomena occur which make satisfactory

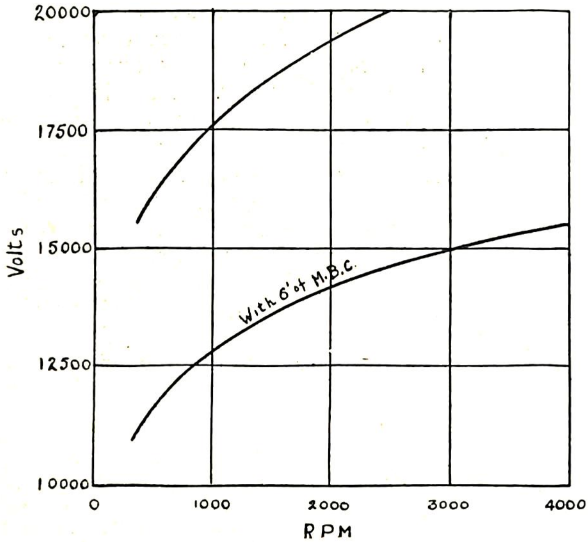

Fig. 20.

operation much more difficult than when the magneto is functioning at ground level. When the electrical stress in air at normal atmospheric pressure exceeds about 27,000 volts/cm. a breakdown occurs and the air no longer remains an insulator. A reduction in air density reduces the breakdown voltage for parallel planes in accordance with the following relation :

Voltage/Pressure = Constant.

When the surfaces between which the electrical stress exists are points or sharp edges, it is possible for a local breakdown to occur in the vicinity of the point or edge without a complete breakdown occurring across the whole field. Under such circumstances the relatively high stress at the point breaks down the air, and this disrupted air, being conducting, covers the point and increases its effective area, giving rise to a reduction in stress and thus preventing a complete breakdown. This partial breakdown is termed a corona or brush discharge, and is enhanced by a reduction in atmospheric pressure. Hence it tends to become progressively worse as the altitude increases.

The effects of corona are to lower the maximum voltage obtainable from a magneto and to produce nitric and nitrous oxides. These oxides may affect the surface insulation of the moulded components, leading to tracking and ultimate breakdown. The bearing grease may also be affected and lead to ultimate failure of the bearings.

The reduction in the maximum voltage obtainable from a magneto at high altitudes is due to the tendency for the discharge to find lower resistance paths within the magneto than through the plug electrodes. Fig. 21 (a) and (b) shows the sparking plug potentials on an aero engine for two different settings of the plug electrodes, the larger setting corresponding to an eroded plug; (c) shows the maximum voltage obtainable from the magneto and indicates that the voltage is limited by a discharge path within the machine, rather than by the circuit constants and primary current. Actually if this discharge path were absent, the magneto would be capable of a considerably higher voltage. It will be noted that curve (b) cuts curve (c) at 38,000 ft., this indicating that the altitude performance of the machine is limited to 38,000 ft. with plug electrodes set to 0·013 in. Similarly from curve (a) the performance is limited to 28,000 ft. with plug electrodes eroded to 0·025 in.

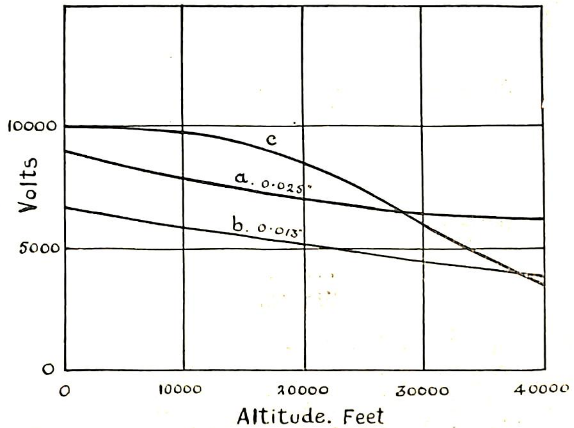

Fig. 21.

From Fig. 21 it is evident that if a good altitude performance is necessary, sparking plug erosion must be avoided, while air and surface factors must be increased above normal to avoid discharges taking place between H.T. parts and earth.

Apart from the possibility of a sparkover in a magneto at low air densities is a tendency for a reduction in voltage due to corona taking place in air trapped in the H.T. winding. Relative to this effect is the necessity of very careful impregnation of the winding. Fig. 22 shows the altitude performance of a coil, firstly imperfectly impregnated, and secondly, after receiving satisfactory impregnation.

In Fig. 25 is shown an enlargement of two distributor electrodes and the rotating electrode of Fig. 27. Assuming the direction of rotation shown, it sometimes happens that at high altitudes the

discharge sparks back to the previous electrode B, in preference to discharging through A. This, of course, produces a misfire. The cause of this phenomenon is a highly-ionised path in the space CB, due to the previous discharge, and a reduction in the normal number of ions available between AC, due to the rarefaction of the air. In order to reduce this tendency, the intersegment distance AB must not be too small and for work at altitudes of 45,000 ft. a distance of some 40 mms. has been found necessary.

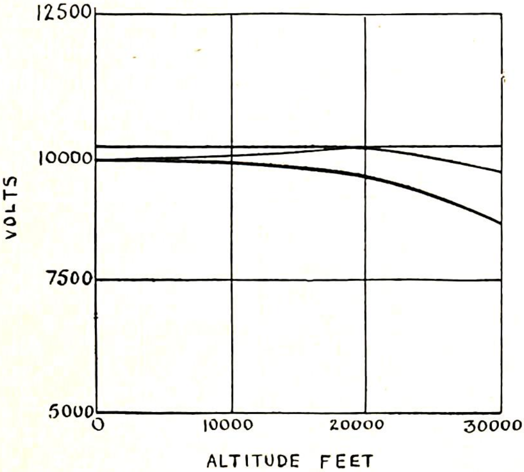

Fig. 22.

Magneto High-Speed Performance.

It has previously been shown that the limiting factor of a magneto's low-speed performance is the primary resistance R_1, and that the higher the rotor speed the less important does this become. It might appear from this, that a magneto will give a satisfactory performance providing its speed is above a certain minimum. This, however, is not so, as will be seen from the following.

Reference to (19) shows that once a spark discharge is initiated it persists for a certain time, depending on the primary current at break, the coefficient of mutual induction between the windings and the voltage across the spark gap. Some values of the voltage once rupture has occurred across the gap of Fig. 29, are given in Table 4.

TABLE 4.

Gap length (mms.)	Volts.
0·25	355
0·5	395
1·0	434
2·0	572

Assuming the contacts to open at the nominal position, the primary current will, in accordance with (15), rapidly decay and be replaced by an equivalent current in the secondary winding decaying in the manner given by (16) in a time given by (19). The remarks just made concerning the behaviour of the secondary current are only strictly true if the rotor could suddenly become stationary at the moment the contacts separate. As the rotor is in motion and the secondary circuit closed by the spark discharge, the conditions are somewhat similar to those of the primary when this is closed, and may therefore be expressed by an equation similar to (20). In the case of the secondary, however, the circuit resistance is extremely high, consisting of that of the winding (about 5000 ohms) and the spark gap, the latter rising from, perhaps, 5000 ohms at the beginning of the discharge to infinity at the end. The effect of this is that very little additional current is induced in the secondary. However, the normal discharge current in the secondary winding produces a magneto motive force which opposes the reversal of the magnet flux in the armature core, delaying its re-establishment. It will at once be appreciated that this may be

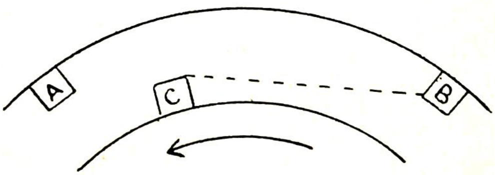

Fig. 23.

detrimental, as a certain amount of demagnetisation of the permanent magnet may take place. Beyond this, however, the effect is not important, providing the secondary discharge has become extinguished before the contacts reclose to produce the next spark. At high speeds the time interval between contact opening and closure is frequently less than the time of secondary discharge, with the result that the secondary is still carrying a current at the moment the contacts reclose. Under these circumstances the secondary current abruptly ceases on contact closure and a current rises with great rapidity in the primary winding. In other words, the energy remaining in the secondary (which would normally appear in the spark) is transferred to the primary winding. The direction of this primary current is that of the current previously in the primary prior to gap rupture and, therefore, similarly to the secondary current, opposes the re-establishment of the core flux. The result is that the flux change for the succeeding primary current is less than under low-speed conditions and in accordance with (23) results in a lowering of I_0. It is evident that if I_0 becomes

too low, due to the above phenomena, misfiring will occur, thus setting a limit to the magneto's high-speed performance.

Another way of regarding the above effect is that the current induced in the primary by the secondary at contact closure delays the generation of the current for the next spark, as the former current is in the opposite direction to the latter. This is clearly shown in Fig. 24, which is an oscillogram from an aero engine magneto running at high speed. The reversed current at contact closure is easily seen. Fig. 25 shows the abrupt cessation of the secondary current as the contacts close and, of course, corresponds to Fig. 24. The cutting of the secondary current clearly shortens the discharge time and reduces the energy per spark.

Improvement of High-Speed Performance.

In dealing with the establishment of the primary current it was stated that an advantage arose from closing the contact breaker at some 30° from the nominal position, without this being detrimental to the value of the primary current at break. The advantage is that by reducing the closed period, the open period may be increased, thus giving the secondary discharge a longer time in which to decay. In general, the closed period may be reduced up to the point at which it commences to affect the value of the current at break and the performance in the retard position.

Sparking Plug Electrode Erosion.

It has been stated previously that one effect of screened cables is to increase the amount of erosion occurring at the sparking plug-electrodes. The effect of this on the altitude performance was shown in Fig. 21. Further effects are the increased stress on the system due to the increase in spark voltage and the necessity of frequent removal of the plugs for gap adjustments. The exact factors controlling plug electrode erosion do not, as yet, appear to be fully understood, but the phenomenon is undoubtedly largely due to the capacity loading produced by screened cables.

The Nature of the Spark Discharge.

It is well known that a magneto spark discharge consists of two distinct parts; an initial discharge corresponding to the quantity stored in the associated capacity of the secondary circuit, and a following discharge of relatively long duration occurring in the comparatively low resistance path prepared by the initial discharge. The latter effect is, of course, shown in Figs. 11 and 12. The initial discharge cannot be observed on the oscillograph owing to its extremely brief existence, this being of the order of 10^{-6} second. The extreme brevity of discharge and the fact that it

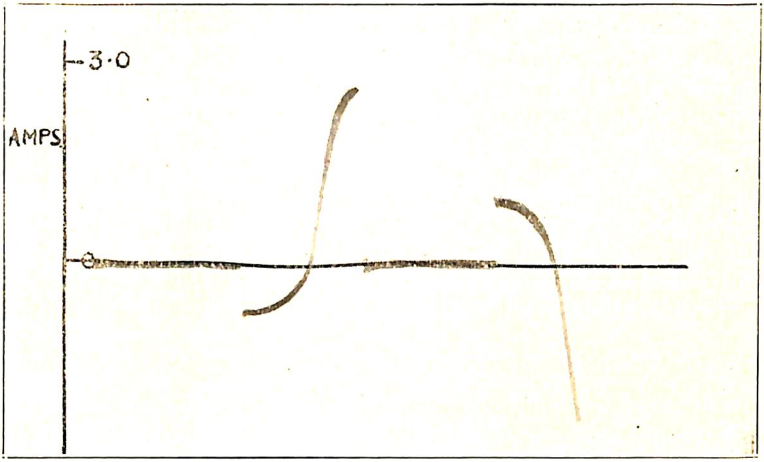

Fig. 24.

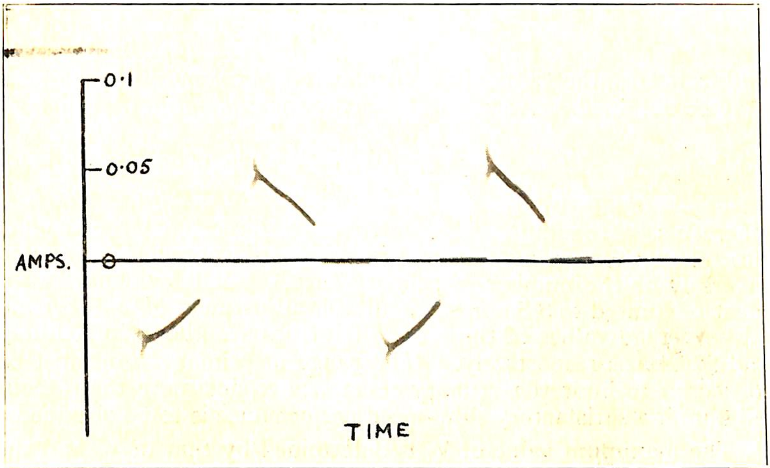

Fig. 25.

occurs in a path of very low or negligible inductance produce relatively enormous currents, which have been estimated by various investigators as ranging from 30 to 150 amperes. It is highly probable that such currents are principally responsible for electrode erosion. An obvious solution appears to lie in the reduction of the magnitude of these currents and in fact does. By placing a resistance of 1000 to 2000 ohms at the plug end of the H.T. cable the erosion is reduced by about 75% and in the case of 6 ft. of braided cable, is no greater than that occurring with plain cables with a similar resistance. No advantage is secured with resistances beyond the values mentioned, nor by inserting such resistances at the magneto end of the cable. The latter is fairly obvious, for the initial discharge current is principally drawn from the cable capacity, increasing in magnitude with distance from the magneto.

The Design and Construction of Ignition Apparatus.

In designing ignition apparatus certain limiting factors must be borne in mind. For example, if reasonable contact life is to be obtained the value of I_0 must not exceed 3·5 amps. for platinum-iridium contacts nor 3·0 amps for tungsten contacts. Also, the value of V_1 must not exceed about 300 volts or sparking, as distinct from arcing, will take place at the contacts. As previously shown, the primary current is given by

$$I_0 = \frac{n_1 (\phi_2 - \phi_1)}{10^8 L_1}$$

and from this, the value of the current to be broken by the contacts may be obtained. Assuming L_1 to vary as n_1^2

$$I_0 = \frac{(\phi_2 - \phi_1)}{a\, n_1}$$

where a is a constant. Hence I_0 varies directly as the magnet flux change occurring during the period of contact closure and inversely as the number of primary turns. It is evident that I_0 must be limited to 3·5 amps. by suitable adjustment of $(\phi_2 - \phi_1)$ and n_1. Average values of these two quantities are about 25,000 lines and 225 turns respectively. The gauge of primary wire must be so chosen to limit the primary resistance to not more than about 0·5 ohm if a satisfactory slow-speed performance is to be obtained.

The maximum value of V_1 is determined by that of V_2 and the secondary/primary turns ratio n. Assuming V_2 to be 10,000 volts and n, 50/1, then V_1 max. would be 200 volts. The values of V_2 and n given above are customary ones. L_1 is usually of the order of 0·025 henry. The size of the secondary wire is generally 45 S.W.G., enamelled.

Coil Construction.

Similar coils are employed for both polar inductor and rotating magnet magnetos. Referring to Fig. 27, the coil is wound on a bakelite or stabilite bobbin, the latter being fixed or moulded on a straight core composed of high-grade electrical sheet steel laminations. The primary winding is first wound and consists of four or five layers of about 20 S.W.G. enamelled wire. This is carefully insulated and winding of the secondary is commenced. This starts at about $\frac{1}{8}$-in. from the bobbin cheek and finishes at the same distance from the other cheek. The wire is wound in layers with a very small air space between individual turns. After each layer is put on, it is covered with a sheet of varnished Japanese rice paper 0·0025 in. thick. This is carried out for four layers, the fifth being covered with 0·006 in. oiled silk. This cycle of five layers is repeated throughout the entire secondary winding. During winding the layers must be frequently subjected to finger pressure to exclude air pockets, as these tend to lead to corona effects. When the full number of secondary turns have been laid on, the coil must be covered with Egyptian tape and vacuum impregnated. To carry out the latter process the coil is first heated in a vacuum chamber for about four hours to eliminate all moisture and air. Following this an oil base varnish is admitted to the impregnating chamber and the vacuum changed to a pressure of about 75 lbs. per sq. in. to force the varnish into the winding. This pressure is maintained for about half-an-hour and the vacuum then reintroduced to draw off the surplus varnish. Finally, the coil is baked at a temperature of 100°C. for 50 hours in an electrically-heated oven provided with good air circulation. The latter is, of course, to ensure thorough oxidation of the varnish.

The Magnetic Circuit.

The magnetic circuit, of which the coil core forms part, is laminated throughout, the pole pieces being cast into the magneto aluminium body. A pole piece lamination assembly, prior to the casting in process, is shown in Fig. 26. It is essential that the casting does not form an unbroken circuit of metal anywhere round the pole piece limbs, for this would produce heavy eddy current losses resulting in a reduction in available primary energy.

It may be mentioned that the iron losses during the period of contact closure are relatively small, as very little flux change occurs during this period. Lamination is necessary to avoid excessive damping during the oscillatory high frequency discharge.

The Distributor.

In order to produce the spark discharges in correct sequence to a multi-cylindered engine, a high tension distributor is necessary.

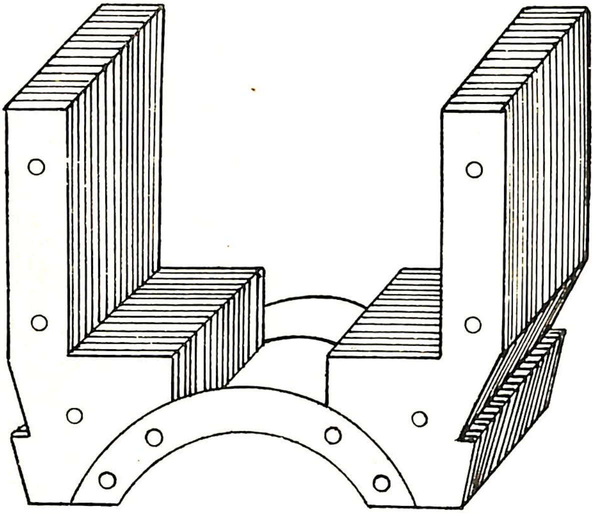

Fig. 26.

This takes the form of a bakelite or stabilite moulding with brass or nickel inserts, as shown in Fig. 27 (a) and (b). In the centre of the distributor is the distributor rotor, a gear-driven moulding carrying a horizontal insert making a rubbing contact at one end with the magneto high-tension winding. The other end of the insert carries a radial electrode having an air gap of about 0·015 in. between its extremity and the fixed electrodes of the distributor. From Fig. 27 (a) it will be noted that the distributor rotor is driven from the magneto rotor, the gear ratio being X/Y, where X is the number of cylinders and Y the number of sparks per rotor revolution. In some cases the distributor is an integral part of the magneto, while in others it is a separate unit. However, in the latter case it must be positively driven and the gear ratio between distributor and magneto rotors must be as above.

It will be noted that two spark gaps exist in the high tension circuit, those of the sparking plug and distributor. The latter is of value in that it helps to shorten the life of the spark discharge and thus promotes re-establishment of the magnet flux in the armature core. When the spark discharge occurs, a volt drop of the same order as those of Table 4 exists across the distributor gap. This increases the value of v_2 in (19), with a consequent reduction in t_d. Furthermore, as the distributor electrodes may not overlap during the whole period of the discharge, the gap between them will lengthen from the moment the electrodes have the relative positions shown at c, Fig. 27. This will, of course, further increase v_2 and reduce t_d.

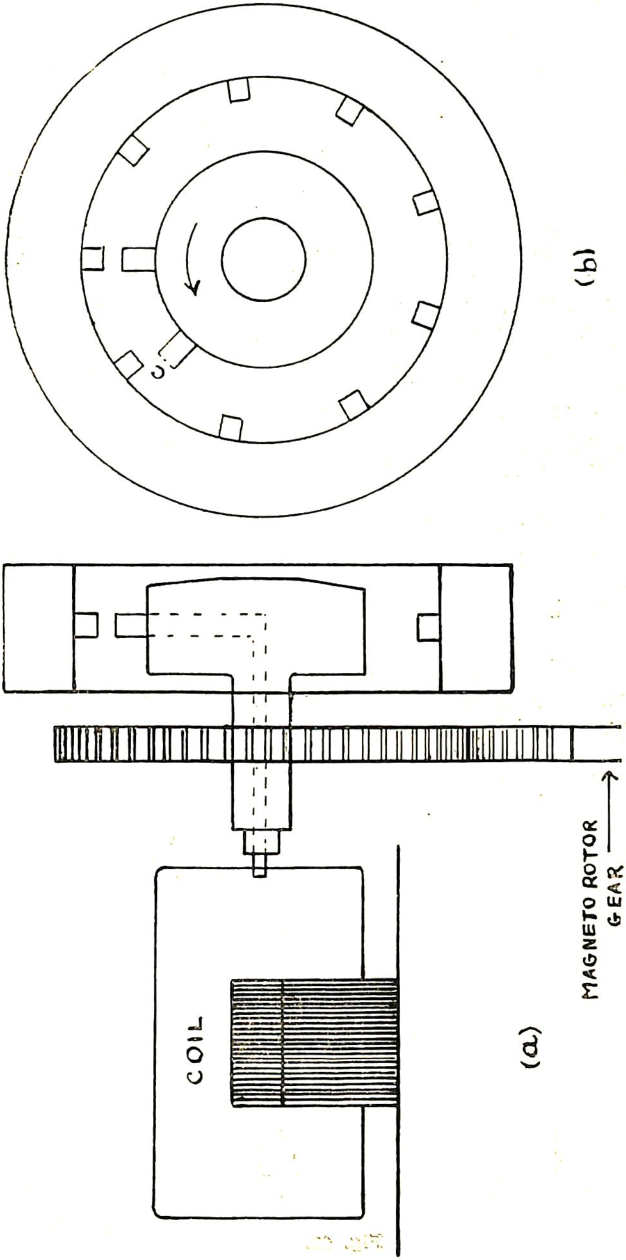

Fig. 27.

The Permanent Magnet.

As previously indicated, the magnetic flux is produced in magnetos by means of a permanent magnet. In the earliest aircraft magnetos this took the form of a horse-shoe, as the magnet steels known at that time required a long length and a comparatively small cross-section to make the best use of their properties. The length required was such as to render a rotating magnet magneto practically an impossibility. The rotating magnet machine has been made possible by the discoveries of cobalt steel and the nickel-aluminium alloys; particularly the latter. At present it is becoming universal practice to employ nickel-aluminium alloys for aircraft, as their use permits a great reduction in size and weight. For example, the weight and volume of alnico is only about one-fifth of that needed of tungsten steel for the same performance. A further advantage of the permanent magnet alloys is their resistance to heat, vibration and demagnetising forces.

Further details of magnets may be found in the author's pamphlet, "Permanent Magnets."

Aircraft Magneto Testing.

As the testing of aircraft magnetos is of a somewhat specialised character, the more important tests and measurements will be now described.

Measurement of H.T. Voltage.

Several alternative methods exist of measuring the magneto secondary potential. The method indicated by Fig. 28 employs

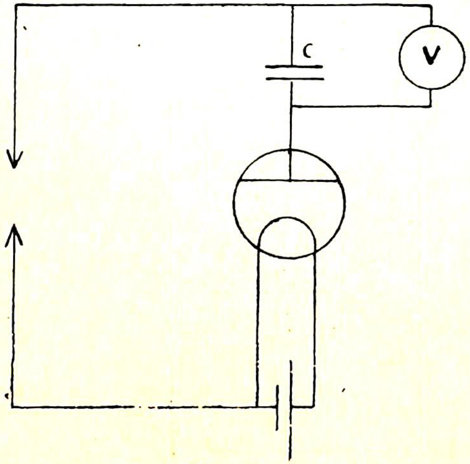

Fig. 28.

an electrostatic voltmeter and a diode rectifying valve. It will be evident that if a series of voltage impulses are applied to the spark gap the condenser C will gradually charge to the maximum value of the voltage providing the upper electrode is positive. The electrostatic voltmeter V will then read the maximum or peak voltage. The insulation resistance of C and V must be of an extremely high order and maintained by enclosing both in a heated box in which is placed some moisture-absorbing substance such as calcium chloride.

The H.T. voltage may be measured by means of a cathode ray oscillograph. As full scale deflection of the oscillograph may occur for about 50 volts, a potentiometer must be employed. A

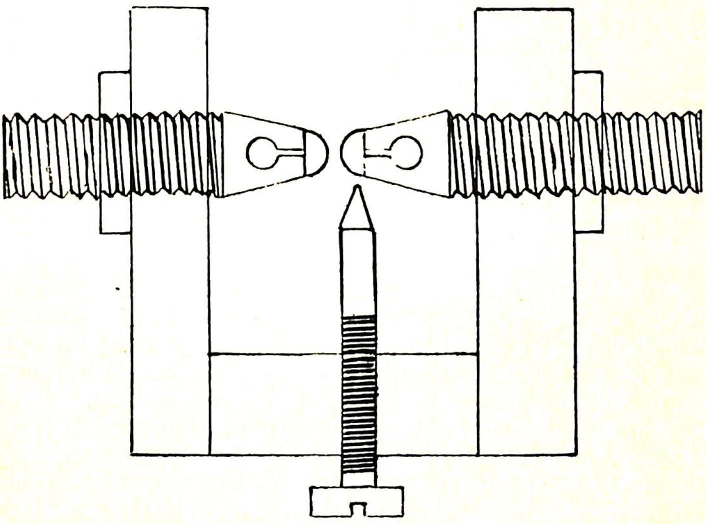

Fig. 29.

suitable arrangement is a 20-megohm resistance shunted across the magneto secondary, the resistance being tapped at about 100,000 ohms. The oscillograph is connected across the latter, due allowance being made for the oscillograph input impedance if necessary.

The two foregoing methods are unsuitable for production or routine testing, and in this case a calibrated spark gap is employed. For aero engine magnetos the gap shown in Fig. 29 is exclusively used. It consists of two $\frac{1}{4}$-in. diameter spring-loaded steel balls, with an insulated brass point situated $\frac{1}{4}$-mm. below and 2 mm. behind the insulated ball. The purpose of the "third point," as it is termed, is to reduce what is known as the impulse ratio of the gap, Impulse ratio may be explained with the assistance of

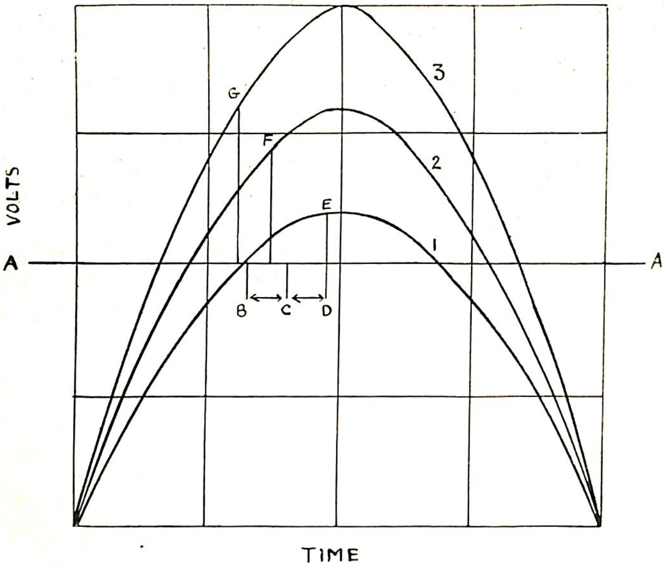

Fig. 30.

Fig. 30. Assume a steady voltage AA to be applied to a gap having a marked impulse ratio. AA represents the breakdown potential of the gap under steady conditions. Now, if the voltage across the gap rises from zero in the manner indicated by Curve 1, the gap will not break down at AA for two reasons. Firstly, before gap breakdown can occur at least one ion must be present in the gap, and secondly, a time period must elapse corresponding to the development of ionisation and gap rupture. The time for ionisation to appear is represented by BC and clearly must be of a fortuitous nature. CD is the time needed for ionisation development. The result of these effects is that under a varying voltage represented by Curve 1 the gap breaks down at E instead of at AA. The ratio E/AA is termed the impulse ratio of the gap. If it be assumed that the period BD is the same for the curves 2 and 3, then with varying voltages applied to the gap represented by these curves breakdown will occur at the points F and G respectively. Hence the greater the rate of voltage rise (or more impulsive waveform), the higher will be the impulse ratio.

It is evident that a gap possessing marked impulse ratio is unsuitable for the measurement of impulse voltages such as those produced by magnetos. The third point reduces the period BD by eliminating the fortuitous part of the period ; *i.e.*, BC. During the rise of voltage to the value AA a brush or corona discharge takes place between the third point and the main electrode, thus

furnishing a supply of ions to the gap. This reduces the impulse ratio and renders the gap more stable.

For the measurement of V_1, the potential across the primary condenser, a cathode ray oscillograph is the most suitable method.

Measurement of Primary and Secondary Currents.

These currents may be measured by means of an oscillograph. For the primary current suitable coils must be fixed to the neck of the cathode ray tube, while there are two alternatives for recording the secondary current. Either coils may be used as for the primary current, or a non-inductive resistance may be placed in series with the earth lead to the spark gap. The oscillograph Y plates are connected across this resistance, a suitable value for the latter being about 500 ohms.

Spark Energy Measurements.

A method of measuring the spark energy content consists of measuring the heat energy per spark. A simple apparatus employed by the writer for doing this is shown in Fig. 31. It consists of a spark gap sealed into a glass tube, which is immersed in a

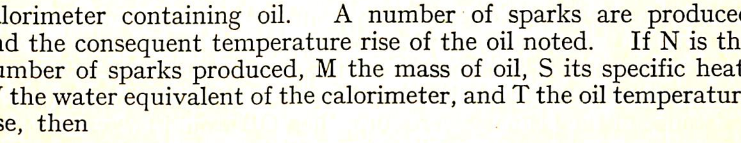

Fig. 31.

calorimeter containing oil. A number of sparks are produced and the consequent temperature rise of the oil noted. If N is the number of sparks produced, M the mass of oil, S its specific heat, W the water equivalent of the calorimeter, and T the oil temperature rise, then

$$J = \frac{4{\cdot}2\ (MS + W)\ T}{N} \text{ joules,}$$

where J is the number of joules per spark.

An oscillographic method of obtaining spark energy and at the same time measuring the flux changes in a magneto will now be described. Across the magneto spark gap is connected a non-inductive resistance in series with a condenser. The X plates of the oscillograph are connected to the condenser, the normal time base not being used. The primary and secondary currents are passed through separate coils fixed to the neck of the tube, the ratio of the number of turns of these coils being roughly the same as those of the magneto primary and secondary windings.

Considering the resistance/condenser circuit, providing the voltage on the condenser is small, we have

$$i = \frac{V_2}{r} = \frac{n_2}{r} \frac{d\phi}{dt} \tag{27}$$

where r is the non-inductive resistance, i the current therein, and $d\phi/dt$ the rate of flux change in the magneto armature.

From (27),

$$idt = \frac{n_2}{r} d\phi$$

If c is the condenser capacity,

$$\frac{idt}{c} = \frac{n_2}{rc} d\phi$$

But $idt/c = dv$, where v is the voltage on the condenser, *i.e.*, the voltage on the X plates.

Therefore

$$dv = \frac{n_2}{cr} d\phi$$

$$\text{and} \quad \Big[v \Big]_{V_1}^{V_2} = \frac{n_2}{cr} \Big[\phi \Big]_{\phi_1}^{\phi_2} \tag{28}$$

From (28) it follows that the change in voltage on the condenser corresponds to a definite flux change in the armature core. The horizontal deflection of the oscillograph may therefore be calibrated in terms of flux. The diagram appearing on the oscillograph due to the simultaneous deflections by condenser voltage and primary or secondary current is similar to that shown in Fig. 32. The flux change OB is that necessary to induce the primary current, while BD is the flux associated with the secondary current. If the resistance of the primary were zero, then OB would be zero and the primary current curve in Fig. 32 would be a vertical line. The length OD is the total flux change in the core and corresponds to $(\phi_2 - \phi_1)$ in (22).

Considering an elementary strip $d\phi$ in Fig. 32, this is equal to $V_2 dt/n_2$ and the area of the strip is therefore $i_2 V_2 dt/n_2$. But the energy associated with the change $d\phi$ is $i_2 v_2 dt$ and therefore the area under the curve BD represents the energy in the spark. Similarly the area under the curve AB represents the energy lost in establishing the primary current.

Variation of Armature Core Flux with Rotor Speed.

It has been shown previously that the persistence of the secondary discharge delays re-establishment of the magnet flux

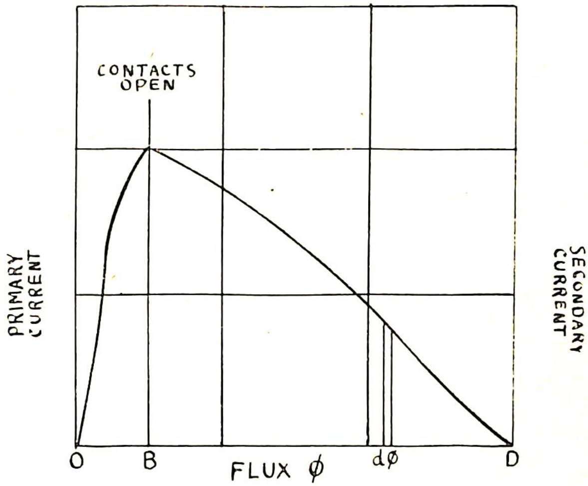

Fig. 32.

in the armature core. At high speeds when the rotor passes the normal position of maximum armature core flux, the magnet flux will generally not be fully re-established in the core due to discharge persistence. If the contacts do not close at this position the fact that the magnet flux commences to decrease will tend to induce a current in the secondary in opposition to the discharge current. Hence the latter will receive an acceleration to its rate of decay and come to an earlier termination, the remaining energy of the discharge being partly dissipated in rotor rotational losses, as beyond the position mentioned, the rotor will tend to motor. If the contacts close during the life of the discharge the effects are similar, for the remaining secondary energy is merely transferred to the primary circuit.

Reference to the oscillograms of Figs. 33 and 34 will show the reduction in resultant core flux occurring at high speeds. In the high-speed figure the reverse primary current at contact closure is clearly shown, as is also the reduction in spark energy. A comparison of the areas under the primary current curves will show the decrease in energy loss in establishing the primary current at the higher speed.

Measurement of Secondary Winding Self-Capacity.

It has been shown previously that one of the determining factors of the maximum potential produced by a magneto is the value of the secondary capacity. Part of this quantity is contained in the self-capacity of the winding and hence the measurement of this

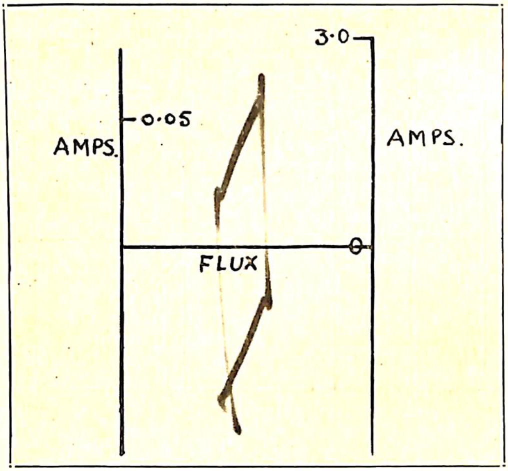

Fig. 33—High Speed. *Figure reads from right to left.*

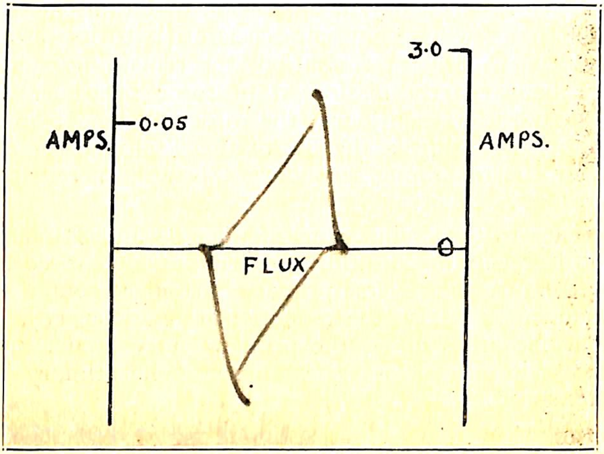

Fig. 34—Low Speed. *Figure reads from right to left.*

latter quantity is important. In proceeding to do this, the coil unit is removed from the magneto and a small current broken in the primary winding, the primary condenser being absent. The secondary winding is connected to an oscillograph and the values of the peaks of the first positive and negative half waves of voltage measured. Let these be P_1 and P_2 respectively. If damping is not excessive, the first two maxima will be reached at times given by $wt = \pi/2$ and $wt = 3\,\pi/2$.

Hence from (6),

$$V_0 = P_1\sqrt{P_1/P_2}$$

Now $\frac{1}{2} L_1 I^2 = \frac{1}{2} C_s V_0^2$ where I is the current above and C_s the secondary winding self-capacity. Hence

$$C_s = \frac{L_1 I^2}{V_0^2} = \frac{L_1 I^2 P_2}{P_1^3}$$

C_s is generally of the order of 0·0001 mf.

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